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D. Wildman, P. Martin, K. Meisner, and H.W. Miller

Fermi National Accelerator Laboratory
P.O. Box 500
Batavia, IL 60510 USA

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BUNCH COALESCING IN THE FERMILAB MAIN RING

D. Wildman, P. Martin, K. Meisner and H. W. Miller
Fermi National Accelerator Laboratory*
P. O. Box 500
Batavia, Illinois 60510

Abstract

A new RF system has been installed in the Fermilab Main Ring to coalesce up to 13 individual bunches of protons or antiprotons into a single high-intensity bunch. The coalescing process consists of adiabatically reducing the h=1113 Main Ring RF voltage from 1 MV to less than 1 kV, capturing the debunched beam in a linearized h=53 and h=106 bucket, rotating for a quarter of a synchrotron oscillation period, and then recapturing the beam in a single h=1113 bucket. The new system will be described and the results of recent coalescing experiments will be compared with computer-generated particle tracking simulations.

Introduction

The process of coalescing a small number of adjacent proton or antiproton bunches into a single high-intensity bunch for injection into the Tevatron collider has been described previously.[1-3] Briefly, it consists of adiabatically lowering the h=1113 Main Ring RF voltage to zero, rotating the debunched beam in an h=53 bucket (linearized with h=106) for a quarter of a synchrotron period, and recapturing the rotated beam in a single h=1113 bucket. An earlier paper[3] illustrated the major problem associated with the coalescing procedure. After a quarter of a synchrotron period, the rotated beam in the h=53 plus h=106 bucket occupied a minimum time spread greater than 40 ns, which is much too long to be recaptured into a single 18.8 ns h=1113 bucket. This excessive time spread resulted in a recaptured central bunch flanked by two smaller bunches of about half the intensity of the central bunch.

Particle Tracking Simulations

In an attempt to understand the origin of the 40 ns minimum time spread, the particle tracking program ESME was used to simulate the actual coalescing conditions. At the beginning of the coalescing process, the individual bunch longitudinal emittance at 150 GeV was approximately 0.16 eV-sec/bunch. After paraphasing the 18 Main Ring cavities, the remaining h=1113 voltage was estimated to be less than 5 kV from measurements of the RF sum signal of all 18 cavity gap voltage monitors. The 5 kV value corresponded to the upper limits of the errors present in the phase and amplitude calibrations of the individual cavity gap-monitors, and the network that combines the individual monitor signals into a total RF sum signal.

Figure 1 shows the ESME longitudinal phase-space plot for the distribution of rotated particles at their narrowest time spread after a quarter of a synchrotron oscillation. The simulation tracked nine bunches of 100 test particles, each with an initial longitudinal emittance of 0.16 eV-sec/bunch. The h=1113 RF voltage has been adiabatically reduced to 5 kV, and the debunched beam was rotated in an RF bucket with an h=53 voltage of 22 kV and an h=106 voltage of 3.75 kV. The solid contour in Fig. 1 is the calculated h=1113 bucket present when the rotated beam is recaptured into a single bunch. Comparing the simulation with our experimental results shows two major differences. First, the fraction of charge computed to be captured in the central single bucket is approximately 50% larger than what was earlier observed. In addition, the plot shows that the majority of charge not captured in the central bunch would also not be captured in the adjcent two RF buckets. The presence of two large "satellite" bunches observed in earlier experiments is not explained by the conditions simulated in Fig. 1.

As a guide to what hardware modifications might make improvements in the coalescing process, the h=1113 voltage limit was lowered from 5 kV to 1 kV in the ESME program. The results are shown in Fig. 2. As expected, the minimum time spread was significantly reduced. Another option was to keep the h=1113 at 5 kV and double the h=53 and h=106 voltages to 44 kV and 7.5 kV respectively. This is illustrated in Fig. 3 where the time spread has been reduced by a factor of $\sqrt{2}$ at the expense of a larger $\Delta p/p$. The effect of both adiabatically lowering the h=1113 voltage to 1 kV, and doubling the h=53 and h=106 voltages is shown in Fig. 4. Since the general behavior of the changes shown in Figs. 2-4 can be easily confirmed by simple calculations, it was decided to build the hardware necessary to both lower the h=1113 voltage and double the h=53 and h=106 voltages.

Modifications to the Coalescing System

To double the h=53 rotating voltage from 22 kV to 44 kV, three additional h=53, 2.5-MHz cavities similar to the three already in use, were installed in the Main Ring tunnel. All of the six 2.5 MHz final power amplifiers were also rebuilt to allow totally remote monitoring and control from outside the tunnel enclosure. This was done in an effort to improve the overall reliability of the amplifiers and reduce the number of tunnel accesses necessary for repairs. The 5 MHz h=106 cavity was previously used at only half of its full output power, so no changes were necessary.

Initially the h=1113 adiabatic voltage reduction was accomplished by dividing the 18 Main Ring cavities into two groups of nine cavities each. The two groups were then paraphased to 180° to produce a net voltage approaching zero. Each set of nine cavities produced a sum voltage of ~500 kV, and small fluctuations in amplitudes and phases of the individual cavities could result in a non-zero net voltage after paraphasing. The coalescing efficiency was very sensitive to this remaining h=1113 voltage and was not consistent from cycle-to-cycle in the Main Ring. The new method of adiabatically reducing the h=1113 RF voltage was based on the assumption that it is easier to achieve a zero net voltage by paraphasing two cavities instead of the entire set of 18 cavities. However, a method still had to be developed which could adiabatically reduce the voltage from an initial value of 800 kV, with all 18 cavities on, to 90 kV with only two cavities. To accomplish this, the Main Ring cavities were divided into four independently controlled groups. Groups A and B each contain eight cavities, while groups A' and B' consist of single cavities. Two phase feedback loops around cavities A' and B' insure that the cavity phases track the low-level RF input signal to within ±0.2°. An RF amplitude feedback loop also maintains equal amplitudes of the paraphasing RF vectors. After acceleration to 150 GeV and cogging the beam bunches

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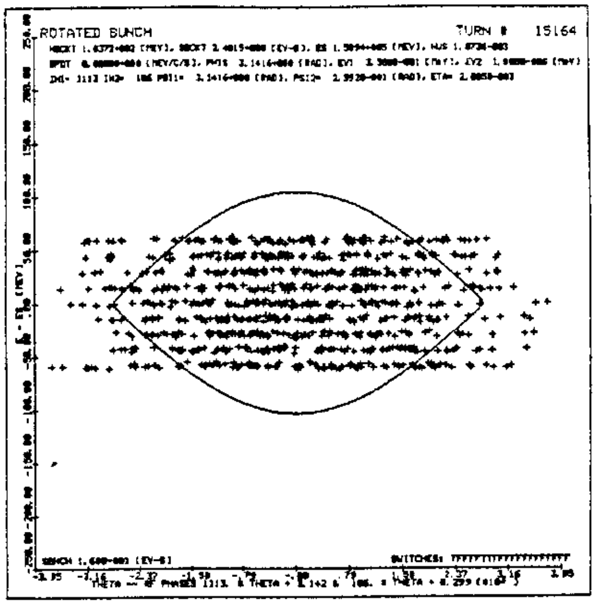

Figure 1. Rotated bunch with h=1113 voltage paraphased to 5 kV, h=53 at 22 kV, and h=106 at 3.75 kV.

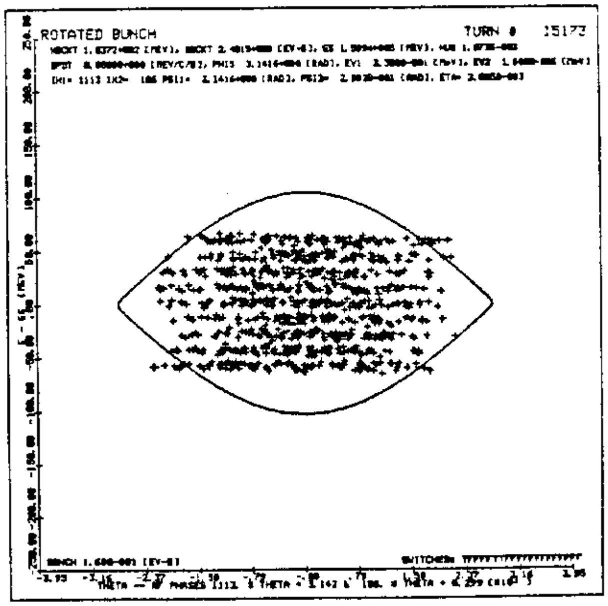

Figure 2. Rotated bunch with h=1113 voltage paraphased to 1 kV, h=53 at 22 kV, and h=106 at 3.75 kV.

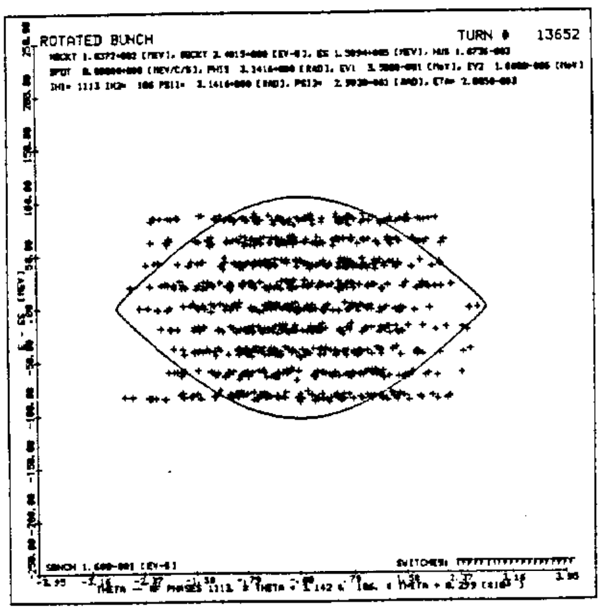

Figure 3. Rotated bunch with h=1113 voltage paraphased to 5 kV, h=53 at 44 kV, and h=106 at 7.5 kV.

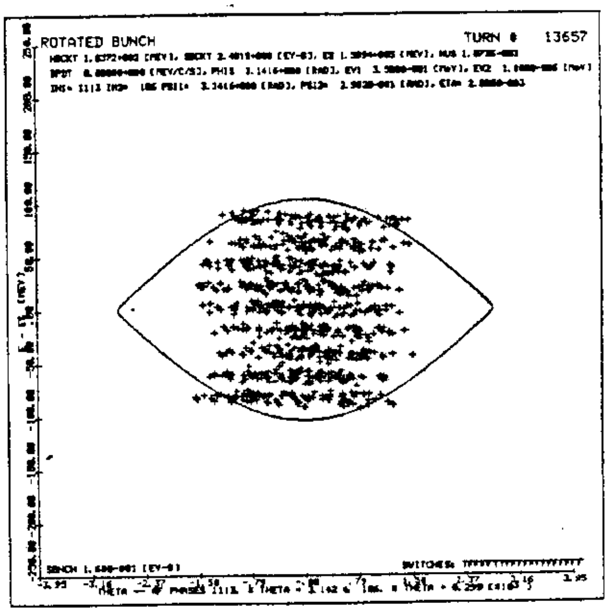

Figure 4. Rotated bunch with h=1113 voltage paraphased to 1 kV, h=53 at 44 kV, and h=106 at 7.5 kV.

to their proper azimuthal position, all 18 cavities are in phase with a net voltage of 800 kV. At the start of the coalescing process, groups A and B are paraphased over a time period of 200 ms to 180°. During this time cavities A' and B' remain in phase with a net sum voltage of 90 kV. At the end of the 200 ms period, the cavity tuning error signals for groups A and B are sampled and held after which the RF drives to the A and B groups are interrupted. Any net voltage resulting from phase or amplitude errors present when groups A and B shut off is small compared to the 90 kV still generated by A' and B', so that the adiabaticity requirement is not violated. With the 16 cavities in groups A and B off, cavities A' and B' are then paraphased to 180°. When the net voltage is zero, the h=53 and h=106 cavities are turned on. After a quarter of a synchrotron period, the RF drives to groups A and B are restored with A and A' in phase, and B and B' in phase. The tuning error signals are again allowed to track the true error signals and groups A and A', and B and B' are immediately moved to 80° to match the h=1113 bucket to the rotated bunch distribution. The h=1113 voltage is then linearly increased during the remaining 200 ms before extraction to match the h=1113 Main Ring buckets to the h=1113 RF buckets already established in the Tevatron.

Experimental Coalescing Results

A design luminosity of 10^{30} $cm^{-2}sec^{-1}$ requires three coalesced proton bunches colliding with three antiproton bunches, each with an intensity of 6×10^{10} particles per bunch. To date, 2.8×10^{10} protons in nine bunches (from a single turn of Booster beam) can be routinely coalesced into a single bunch with no satellite bunches. Using two turns of Booster beam, the largest single proton bunch observed had an intensity of 5.7×10^{10} and is shown in Fig. 5. The oscilloscope traces in Figs. 5 and 6 show the single bunch intensity signals from two 2-GHz bandwidth resistive wall current monitors. The traces are taken every ten machine revolutions with the top three traces showing beam in the Main Ring being transferred into the Tevatron (lower inverted signals). The apparent increase in intensity during the transfer is an artifact produced by the higher sensitivity of the Tevatron monitor.

The coalescing efficiency, which is defined as the fraction of initial particles coalesced into a single bunch, is a strong function of the beam's initial longitudinal emittance at 150 GeV. Recent emittance measurements yield 0.12, 0.21, and 0.28 eV-sec for 1, 2, and 3 turns (2.7×10^{10}, 5×10^{10}, 7×10^{10} protons/8 bunches) of Booster beam. Measurements taken on the same Main Ring cycles show that the coalescing efficiency drops from ~100% at 0.12 eV-sec to ~60% at 0.28 eV-sec. When the efficiency drops to 60%, two small satellite bunches containing ~25% of the beam appear. In agreement with the ESME calculations, the remainder is not captured in any RF buckets. Currently, the antiproton coalescing efficiency is greater than 80%, with the maximum bunch intensity limited by the number of antiprotons being accelerated to 150 GeV in the Main Ring. Figure 6 shows a single antiproton bunch with an intensity of 4.2×10^{10} being transferred from the Main Ring to the Tevatron.

When coalescing nine bunches, the beneficial effect of the linearizing h=106 cavity has been difficult to determine. The 5% increase in efficiency predicted by ESME with the h=106 cavity operating has not been observed, and most of the data has been taken without the h=106 voltage present. Future plans call for more detailed studies of the effect of the h=106 cavity with the goal of maintaining a high efficiency, while increasing the number of bunches coalesced from nine to eleven or thirteen.

Acknowledgements

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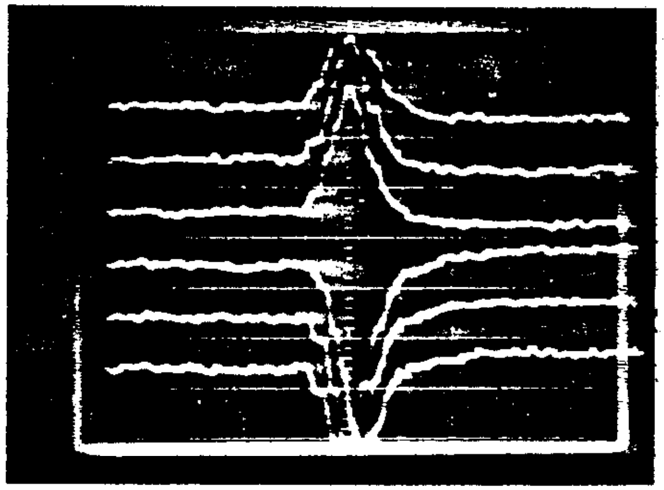
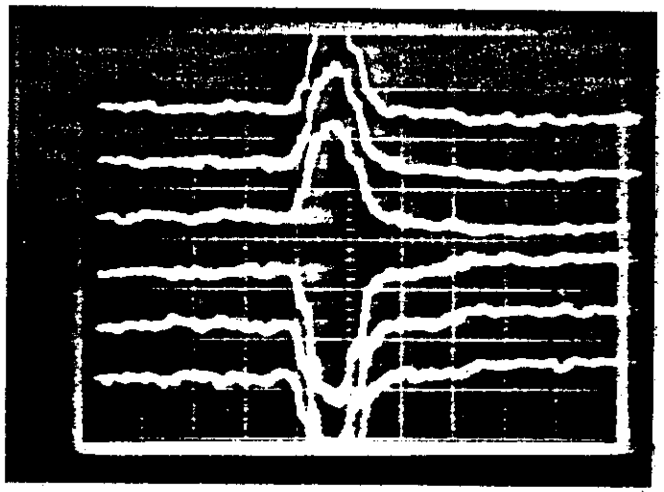


10 ns/div.

Figure 5. Transfer of a coalesced bunch of 5.7×10^{10} protons from the Main Ring into the Tevatron.



10 ns/div

Figure 6. Transfer of a coalesced bunch of 4.2×10^{9} antiprotons from the Main Ring into the Tevatron.